LINAC-BASED SHORT WAVELENGTH FELS

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Abstract

The main issues related to the realization of short wavelength (i.e. UV, VUV and X) free-electron lasers (FEL) driven by electron beams generated by linacs are investigated. The scenario of existing and planned devices is discussed and compared with the need of experimental test check points for the schemes proposed for the realization of very short wavelength radiation sources.

1. INTRODUCTION

About twenty years ago the first free-electron laser (FEL) amplifier has been operated in Stanford by J.M.J. Madey and co-workers. Starting from that time, new (but not so many!) FEL sources have been realized and operated in a quite wide spectral region, ranging from microwaves to UV [1]. As previously underlined, only a limited number of FELs has been realized (namely only few tens of devices). The reason of this so unusual *phenomenon* in the laser field is related mainly with two problems:

1. FELs are expensive devices (for both realization and operation)
2. a wide spectrum of knowledge is required for the realization of a FEL (accelerators, magnets, optics)

In addition we must take into account that *conventional lasers* cover now a large part of the spectrum in the infrared, visible and UV region with relatively inexpensive and reliable devices. As a consequence, the interest in the development of FEL sources is mainly related to the possibility to operate in regions not covered, with comparable performances, by other conventional lasers. The most interesting regions, under this point of view, are the medium and far infrared in the long wavelength part of the spectrum and VUV and soft X-rays in the short one. In this paper will focus our attention on one particular kind of devices, i.e. the linac-based short wavelength FELs.

2. UV-VUV-X SOURCES: FEL PARAMETERS AND STATE OF THE ART

The generation of short wavelength radiation via a single passage linac-based FEL can be achieved by utilizing various schemes. Up to now only the oscillator configuration has been exploited. As we shall see in the next section, this scheme cannot be utilized at very short wavelength. Other two quite promising configurations have been proposed and are now under theoretical and experimental investigation,

1. high gain harmonic generation (HGHG)
2. self amplified spontaneous emission (SASE)

With these kind of configurations it will be possible, as we shall see in the following, to push the operating region down to few tens of nm and to a fraction of nm for HGHG and SASE respectively (see fig. 1). Theory and modelling of all these three devices (oscillator, HGHG and SASE) can be found in references [2]. In this section we shall discuss the status of the art and the main issues related to their realization.

2.1 Operating Wavelength

One of the main characteristics of the FEL is its tunability. Namely the radiation wavelength (λ) depends on a set of parameters (electron energy (E) and magnetic field magnitude (B) and period (λ_u)) that can be more or less easily adjusted in order to cover a very broad band spectrum. The well know equation that relates the wavelength to these parameters reads (for linear undulators),

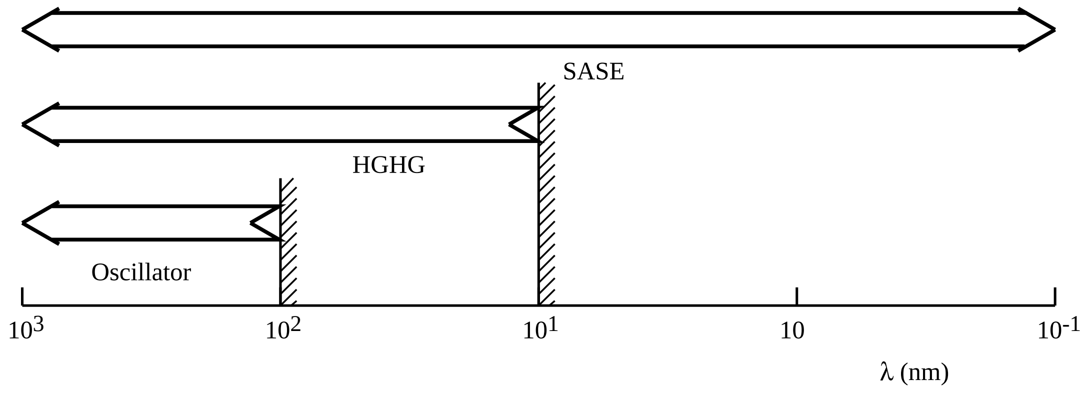

Fig. 1 - Operating regions for FEL oscillators, high gain harmonic generation devices (HGHG) and self amplified spontaneous emission devices (SASE)

$$\lambda = (\lambda_u/2n\gamma^2)(1 + K^2) \qquad (1)$$

where we utilized the usual notations (m = rest electron mass, c = ligth speed in vacuum)

γ = relativistic factor = $E/(mc^2)$
$K = eB\lambda_u/(2\sqrt{2}\pi mc^2)$
n = 1,3,5,... harmonic number

From eq. (1) we derive that, with undulators of few centimeters period and $K \approx 1$, we need electrons with energy of the order of $\approx$ 100 MeV for the operation in UV, and up to many GeV for the X region. All this full range is now, in principle, available and, as we shall see in the next sections, the Status of the Art of the electron beam technology could allow, in the near future, the operation of FEL devices down to $\lambda = 0.1$ nm.

2.2 FEL Oscillator

The feasibility of a FEL oscillator is, first of all, related to the availability of mirrors with good reflectivity (at least on the order of 10%) to be utilized for the implementation of low losses optical cavities. At the present stage of the technology the lower limit for the wavelength is around 100 nm. Namely the minimum wavelength up to now reached is λ = 240 nm, obtained with the storage-ring-based FEL in Novosibirsk [3], while, for linac-based devices, the record (320 nm) has been reached in FELI (Osaka) [4]. Typical operating region for a FEL oscillator is the so-called *low gain regime*. In this condition the maximum gain in first harmonic (n = 1, see eq. (1)) in small-signal regime (1-D approximation) is given by,

$$G = (1.5/\sqrt{2})(2\pi N\rho)^3/((1 + \mu_c/3)(1 + \mu_x^2) \times \\ \times (1 + \mu_y^2)(1 + 1.7\mu_E^2)) \qquad (2)$$

where we have defined

$$\rho = \textit{Pierce parameter} = \\ (((\lambda^{3/2}\lambda_u^{1/2})/(\sqrt{2}\, 4\pi\Sigma))\,(K^2/(1 + K^2)^{3/2})(I/I_o)[JJ])^{1/3} \qquad (3)$$

N = number of undulator periods
Σ = radiation mode cross section $\approx \lambda L$
L = undulator length
I_o = Alfvèn current = 17 kA
$[JJ] = (J_o(\xi) - J_1(\xi))^2$ = Bessel function factor for linear undulators

The terms in the denominator of eq. (2) account for the gain reduction due to the finite electron bunch length ($c\tau$) and to the electron energy spread ($\Delta E/E$) and emittances ($\varepsilon_{x,y}$),

$$\mu_c = \lambda N/(c\tau), \quad \mu_{x,y} = 2N\varepsilon_{x,y}/((\lambda\lambda_u/h_{x,y})(1+1/K^2))^{1/2}, \\ \mu_E = 4N(\Delta E/E) \qquad (4)$$

($h_{x,y}$ = sextupolar terms of the undulator magnet)

From eqs. (3) and (4) we derive that the gain strongly depends on the wavelength. Namely, in order to avoid gain degradation, the coefficients (eqs. (4)) that measure the slippage between electrons and photons (μ_c) and the inhomogeneous broadening due toenergy spread (μ_E) and emittances ($\mu_{x,y}$) with respect to the FEL gain bandwidth (1/(2N)), must be negligible with respect to the unity. As a consequence the electron beam parameters must satisfies the following inequalities,

$$\tau >> \lambda N/c \qquad (5)$$

$$\Delta E/E << 1/(4N) \qquad (6)$$

$$\varepsilon_{x,y} << (1/(2N))((\lambda\lambda_u/h_{x,y})(1+1/K^2))^{1/2} \qquad (7)$$

In addition we must take into account that eq. (3) has been derived in 1-D approximation. In order to avoid that 3-D effect can reduce the gain, we must require that the electron beam cross section would be smaller than the radiation lowest order mode one, i.e.

$$\varepsilon_{x,y} << \lambda/4\pi \qquad (8)$$

Equation (5) is easily satisfied in the short wavelength region, while eqs. (7) and (8) are heavier to satisfy as the wavelength decreases. In the mean time the gain coefficient ρ^3 decreases with the wavelength. A further problems arises from the strong decreasing of the mirror reflectivity at short wavelength, as stressed previously. Taking into account all these problems and the state of the art of electron sources and optics, the lower limit for the operation of a FEL oscillator can be estimated around 200-100 nm. Competition with existing standard lasers and storage ring based FELs will affect strongly the future of this kind of sources that, with respect to standard lasers, exibit a quite large tunability and, with respect to storage ring based FELs, a larger average and peak power. In Tab. 1 it is reported the scenario of the existing and planned UV FEL linac-based oscillators. Up to now only two sources have been operated (in Los Alamos (USA) and in FELI (Osaka,J)) and one (wich will be operated around 200 nm in third harmonic) is under realization at Boeing in Seattle (USA). For shorter wavelengths (i.e. shorter than 200-100 nm) different approches, based on high gain single passage devices (see next sect.), are needed.

Tab. 1. Linac based UV FEL oscillator devices

	Ref.	*λ[nm]*	*τ[ps]*	*P[MW]*	*<P>[W]*	*λ_u[cm]*	*E[MeV]*	*I [A]*	*comments*
LASL(USA)	[5]	380	6	25	36	1.36	45	135	operating
FELI (J)	[4]	350	1.7	1.8	67	2.2	144	60	operating
BOEING (USA)	[6]	>200	7	≈ 0.15	≈ 1000	2.18	120	500	3rd harm. (in constr.)

2.3 High Gain Operation

In high gain regime the evolution of the laser power P along the undulator follows an exponential law,

$$P \propto (P_o/9)\exp(z/L_G) \qquad (9)$$

where P_o is the input power (from an external source or related to the spontaneous emission), z is the longitudinal coordinate and L_G is the *gain length* defined as (ρ is the Pierce parameter defined in eq. (3)),

$$L_G = \lambda_u/(4\sqrt{3}\,\pi\rho) \qquad (10)$$

For enough high ρ values there are many *gain lengths* L_G along the undulator, so that it is possible to have very high integrated gain in one passage. For example, in Livermore [7], amplification up to 40 dB has been obtained in a FEL operating in the millimeter wavelength region. The order of magnitude of the "*enough high ρ*" can be easily derived from eq. (10). Namely the gain length and the undulator period are of the order of some meters and some centimeters respectively, so that ρ (for an *ideal beam*!) must be of the order of 10^{-3}, which corresponds to a peak current on the order of some kA. However we have to take into account that 3-D effects, energy spread and emittance can heavily affect the gain. Namely the electron beam cross section must be smaller than the radiation fundamental mode one (eq. (8)), the diffraction must be negligible in one gain length (β = betatron function),

$$L_R = \text{Raleigh length} = 4\pi\varepsilon\beta/\lambda \geq L_G \qquad (11)$$

and the inhomogeneous broadening due to energy spread and emittance must be negligible with respect to the FEL gain bandwidth, which is given just by the Pierce parameter ρ,

$$\Delta E/E << \rho/2 \qquad (12)$$

$$\varepsilon_{x,y} << \rho((\lambda\lambda_u/h_{x,y})(1+1/K^2))^{1/2}\ , \qquad (\gamma\varepsilon_{x,y} << \rho(\lambda_u/\sqrt{(2h_{x,y})})(1+K^2)/K) \qquad (13)$$

By combining eq.(8) with eq. (11) we derive that the gain length must be shorter than the β–function in order to reduce 3-D effects,

$$L_G < \beta \qquad (14)$$

which requires again L_G of the order of a meter ($\rho \approx 10^{-3}$) when β ≈ some meters. Finally eq. (12) and (13) require an energy spread of the order of 10^{-4} and a normalized emittance $\gamma\varepsilon_{x,y}$ (for $\lambda_u \approx$ cm, $h_{x,y} \approx 1$, $K \approx 1$) less than 10 mm mrad. All this kind of requests appeared some years ago very heavy to satisfy. Recently the situation is strongly changed. Namely, the dramatic improuvements of the performances of high energy accelerators, developed for elementary particle physics, make now possible the realization of FEL devices which utilize electron beams operating in the kA, GeV current and energy range with normalized emittance on the order of 10^{-6} m rad. This improuvement is mainly related to the developing of laser driven RF phtocathode guns [8], which provide, with respect to the traditional thermoionic injectors, very high brightness electron beams that can be directly accelerated by RF structures, so avoiding emittance growth due to phase space dilution during the bunching process. Namely all the UV-X FEL devices now under development (see Tab. 2) utilize electron beams generated with this technique.

The FEL reported in Tab. 2 are based on two different schemes. For the UV-VUV region both HGHG and SASE can be utilized, while in the X region only SASE can be exploited, due to the lack of suitable coherent sources (see fig. 1). In the HGHG [13] scheme (planned at the DUV device in BNL) the electron beam interacts in a first undulator with a resonant laser beam, which induces a density modulation at the fundamental, as well as at the higher harmonics of the input laser beam. Then, eventually after a dispersive section that enhances the bunching, the electron beam is sent into a second undulator which is resonant at a higher harmonics (typically the 3rd or the 5th). Due to the harmonic modulation, the electron beam radiates coherently and an exponential blow-up of the radiation takes place. In addition the coherence of the output radiation is quite high, namely it has the same quality of that of the input one. The bottle-neck of this scheme is the input laser, which could be limited to operate at very low duty cycle and, normally, does not exibit good tunability. In order to overcome this problem, a different scheme has been proposed [14], in which the bunching is provided by previously utilizing the electron beam as active medium in a FEL oscillator operating in the UV region, where

Tab. 2. Linac based VUV-X rays HGHG and SASE FEL devices

	Ref.	*λ[nm]*	*τ[ps]*	*P[MW]*	*<P>[W]*	*$λ_u$[cm]*	*E[MeV]*	*I[A]*	*comments*
BNL (USA)	[9]	200	6	140		3.89	210	300	seed (800kW)
(DUV-FEL)		200	6	70		3.89	210	300	HGHG (400nm)
		<200	6	70		3.89	310	300	seed (140nm)
		<100	6			3.89	310	300	HGHG (5fs,80nm)
ARGONNE (USA)	[10]	300	3			0.3	50	600	SASE
DESY(G) (TESLA FEL)	[11]	6	0.17	1400	40	2.73	1000	2400	SASE
SLAC(USA)	[12]	3	0.3	10000	1	8	7000	2500	SASE
(LCLS)		0.15	0.250	50000	1.6	3	15000	5000	SASE

enough good reflectivity mirrors are available, and than, like in the HGHG, by injecting the bunched beam in an undulator resonant at an harmonic of the first FEL. In this configuration a quite high average power tunable radiation could be generated down to 100-50 nm.

SASE [15] is the only way to operate a FEL in the X region, where no input laser beam (standard or FEL) are available. In SASE configuration the seed for the start up is provided by the spontaneous emitted power. The output radiation has a temporal coherence of the same kind of the spontaneous one [16], while, if condition (8) is satisfied, it has a fully transverse coherence. It is worth to stress that when condition (8) is not satisfied, higher order transverse modes can have enough gain to be excited, and, as a consequence, there could be not only a lowering of the gain on the fundamental mode but a degradation of transverse coherence too.

3. CONCLUSIONS AND OUTLOOKS

Following what reported in the previous section, the field of short and very short wavelength linac driven FELs appears quite challenging and promising. Namely the UV VUV region could be covered with tuneble, high power devices, with capability to operate also in the femtosecond range, while the utilization of multi-GeV, multi-kA, very low emittance and energy spread electron beams opens the possibility to realize X-rays FELs whose performances will overcome largely that of existing and planned conventional synchrotron radiation sources. However, it must be stressed that a lot of theoretical and experimental work (in particular for X-rays devices) has still to be done. Namely scaling laws relevant to SASE must be experimentally checked at short wavelengths, in order to avoid to make a single jump of too many order of magnitude ($\approx 10^7$) that there are between the existing devices and the planned ones [17]. If the experimental tests will confirm the performances now expected for linac driven X FELs, in particular in terms of brilliance, see fig. 2, there is a quite wide agreement on the fact that this technology will be very competitive, with respect to the classical storage ring configuration, for the fourth-generation light sources, at least up to photon energy of the order of 10 keV [18].

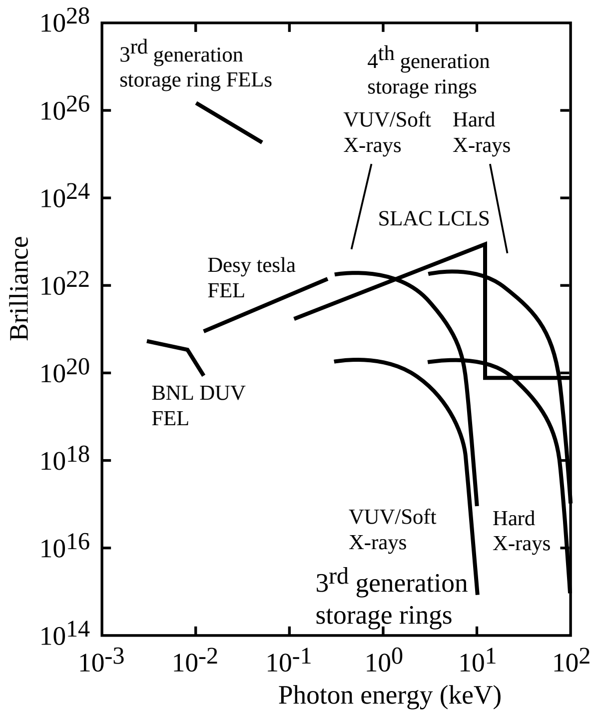

Fig. 2 - Average spectral brilliance [photonsxs^{-1} mm^{-2} mrad^{-2} (0.1% Bandwidth)$^{-1}$] of third and fourth generation Storage Rings compared with FEL performances (from Ref. [18] p. 21)

4. REFERENCES

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